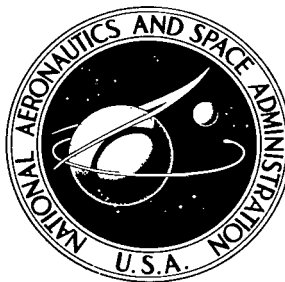


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USE OF A SIX-DEGREES-OF-FREEDOM  
MOTION SIMULATOR FOR  
VTOL HOVERING TASKS

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<b>16. Abstract</b> <p>A piloted, six-degrees-of-freedom motion simulator has been evaluated with regard to its ability to simulate VTOL visual hovering tasks. Characteristics of the variable stability jet-lift Bell X-14A aircraft were simulated, and results for the roll and pitch axes were compared with flight data. The roll-axis data were also compared with data from two- and single-degree of-freedom simulators.</p> <p>Control power and damping requirements for the roll and pitch axes compared very well with flight data. The simulator's motion quality was considered outstanding for VTOL hovering flight. Its travel limits were large enough to simulate hover-maneuver tasks on a one-to-one scale.</p> <p>Roll-lateral motions (two-degrees-of-freedom motions) gave essentially the same results as six-degrees operation for evaluation of roll-axis maneuvers.</p>			
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# USE OF A SIX-DEGREES-OF-FREEDOM MOTION SIMULATOR FOR VTOL HOVERING TASKS

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## SUMMARY

A piloted, six-degrees-of-freedom motion simulator has been evaluated with regard to its ability to simulate VTOL visual hovering tasks. Characteristics of the variable-stability jet-lift Bell X-14A aircraft were simulated, and results for the roll and pitch axes were compared with flight data. The roll-axis data were also compared with data from two- and single-degree-of-freedom simulators.

Control power and damping requirements for the roll and pitch axes compared very well with flight data. The simulator's motion quality was considered outstanding for VTOL hovering flight. Its travel limits were large enough to simulate hover-maneuver tasks on a one-to-one scale, that is, without the need for any attenuation of the drive signals.

Roll-lateral motions (two-degrees-of-freedom motions) gave essentially the same results as six-degrees operation for evaluation of roll-axis maneuvers.

## INTRODUCTION

The application of piloted ground-based flight simulators to the study of problems associated with VTOL aircraft in hovering flight has now undergone at least a decade of serious development. During that time, some highly sophisticated VTOL simulators have evolved, and the simulation technique is now considered as important to the study of handling qualities as the wind tunnel is to the study of aerodynamics. Despite this success, efforts persist to develop VTOL simulation to a higher degree of usefulness. Past simulations have served primarily to demonstrate the relative importance of design parameters, and the requirement now is for simulations that are more effective in establishing the effects of individual parameter magnitude.

All ground-based simulators have inherent limitations that detract from realism and, consequently, inhibit the ability to obtain data applicable to flight. For example, even those simulators with motion capability cannot possibly provide the pilot with sufficient travel for him to perform a very wide variety of realistic evaluation tasks. Therefore, washouts (i.e., filters) must be superimposed on their drive signals to attenuate the commanded

displacement (ref. 1). These washouts are generally designed to permit good reproduction of initial accelerations, but subsequent motions may be considerably out of phase with the commands. In the hovering task, motion fidelity, or lack of it, has such a pronounced effect that a better alternative may be no motion at all, if the required washouts are too severe.

The usefulness of the piloted simulator is also affected by limitations of the visual presentation. Shortcomings in the artificial visual scenes used in the past have been particularly detrimental to VTOL simulation. The prime requirements of a wide field of view and clarity at low altitude tend to be mutually exclusive, and the physical characteristics of systems that provide a good compromise of those features make them incompatible with an adequate motion system. A real world visual presentation would seem to be highly desirable, but that is possible only when the motions are reproduced in true full scale.

The Ames six-degrees-of-freedom motion simulator shown in figure 1 was designed to overcome problems of motion and visual requirements such as those described above for the hovering task. This device has the capability of traversing an 18-foot cube of space, making it possible to perform small hovering maneuvers without the use of motion washouts, and without the need for an

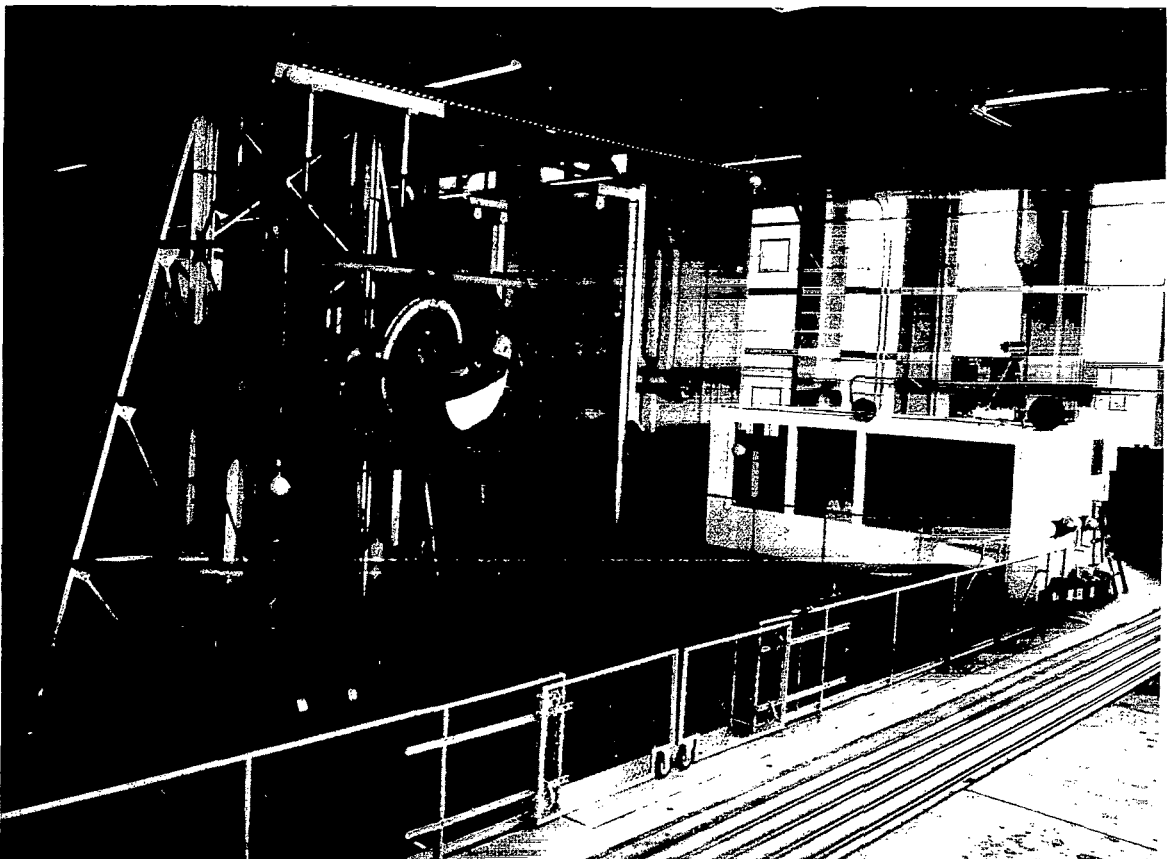


Figure 1.- Ames six-degrees-of-freedom simulator.

artificial visual system. To determine the ability of the simulator to perform research in the hovering flight regime, it was compared with the X-14A aircraft during concurrent operation on an identical research problem. The results of that comparison are the main subject of this report.

Secondary to the comparison experiment, the effects of decreasing the degrees of motion freedom were evaluated by repeating a portion of the six-degrees-of-freedom program in two- and single-degree motions. Such information may be helpful to operators of less elaborate simulation equipment.

#### NOTATIONS

dB	decibel, $20 \log_{10}$ (output amplitude/input amplitude)
g	acceleration due to gravity, $32.2 \text{ ft/sec}^2$
$I_x$	roll moment of inertia, $\text{slug-ft}^2$
$I_y$	pitch moment of inertia, $\text{slug-ft}^2$
$I_z$	yaw moment of inertia, $\text{slug-ft}^2$
$I_{xz}$	product of inertia, $\text{slug-ft}^2$
L	rolling moment (right wing down, positive), lb-ft
$L_p$	partial derivative of rolling moment with respect to roll-rate, lb-ft/radian/sec
$\frac{L_p}{I_x}$	roll-rate damping, 1/sec
$L_\delta$	rolling moment per unit of controller deflection, lb-ft/in.
$\frac{L_\delta}{I_x}$	roll-control sensitivity, $\text{radians/sec}^2/\text{in.}$
$\frac{L_\delta \delta_{\max}}{I_x}$	roll-control power, $\text{radians/sec}^2$
m	airplane mass, slugs
M	pitching moment (nose up, positive), lb-ft
$M_q$	partial derivative of pitching moment with respect to pitch-rate, lb-ft/radian/sec
$\frac{M_q}{I_y}$	pitch-rate damping, 1/sec

$M_{\delta}$	pitching moment per unit of controller deflection, lb-ft/in.
$\frac{M_{\delta}}{I_y}$	pitch-control sensitivity, radians/sec <sup>2</sup> /in.
$\frac{M_{\delta}\delta_{\max}}{I_y}$	pitch-control power, radians/sec <sup>2</sup>
$N$	yawing moment (nose right, positive), lb-ft
$N_r$	partial derivative of yawing moment with respect to yaw-rate, lb-ft/radian/sec
$\frac{N_r}{I_z}$	yaw-rate damping, 1/sec
$N_{\delta}$	yawing moment per unit of controller deflection, lb-ft/in.
$\frac{N_{\delta}}{I_z}$	yaw-control sensitivity, radians/sec <sup>2</sup> /in.
$\frac{N_{\delta}\delta_{\max}}{I_z}$	yaw-control power, radians/sec <sup>2</sup>
PR	pilot rating
$p$	roll rate about body axis (right wing moving down, positive), radians/sec
$q$	pitch rate about body axis (nose moving up, positive), radians/sec
$r$	yaw rate about body axis (nose moving right, positive), radians/sec
$T$	thrust, lb
$u$	body-axis longitudinal velocity (moving forward, positive), ft/sec
VTOL	vertical takeoff and landing
$v$	body-axis lateral velocity (moving to right, positive), ft/sec
$w$	body-axis vertical velocity (moving down, positive), ft/sec
$X$	inertial-axis longitudinal displacement, ft
$Y$	inertial-axis lateral displacement, ft

Z	inertial-axis vertical displacement (toward earth, positive), ft
$\delta$	controller deflection, in.
$\delta_{\max}$	maximum controller deflection, in. (see table II)
$\theta$	body-axis pitch angle, radians
$\phi$	body-axis roll, radians
$\tau$	time constant, sec
$\psi$	body-axis yaw angle, radians
$(\dot{\phantom{a}})$	$\frac{d(\phantom{a})}{dt}$

#### Subscripts

a	aileron
e	elevator
G	simulator reference axes system (gimbal axes)
r	rudder
t	throttle

#### SIMULATOR

The Ames six-degrees-of-freedom simulator is shown in figure 1 and its motion capabilities are summarized in table I. The simulator is free to travel within a cube that is approximately 18 feet on a side, and the angular modes have the capability of  $\pm 45^\circ$  of motion. The gimbal structure supporting the cab rides on nylon rollers up and down a pair of vertical rails. These rails are attached to a tower structure, which rides on steel rollers along four longitudinal rails. This entire mass, amounting to approximately 79,000 lb, rides on steel rollers along six lateral rails.

The angular and linear modes are powered by electric motors in Ward-Leonard type servo systems (ref. 2). Silent chains transfer power from the drive motors to rubber-faced sectors for angular motions, and cables pulled by drums transfer power to the linear modes.

For this investigation, the simulator was driven by direct current signals generated in an analog computer. As the pilot operated the cockpit

controls, the computer solved the aircraft equations of motion, transformed the computed velocities from airplane body-axes into simulator reference-frame-axes, and integrated the results to obtain simulator position drive signals. These signals were then modified by the addition of acceleration and velocity terms to the position drive signals for the purpose of servo equalization. The complete simulator drive system is represented in figure 2, and frequency response data for the roll, pitch, longitudinal, and lateral motions are provided in appendix A.

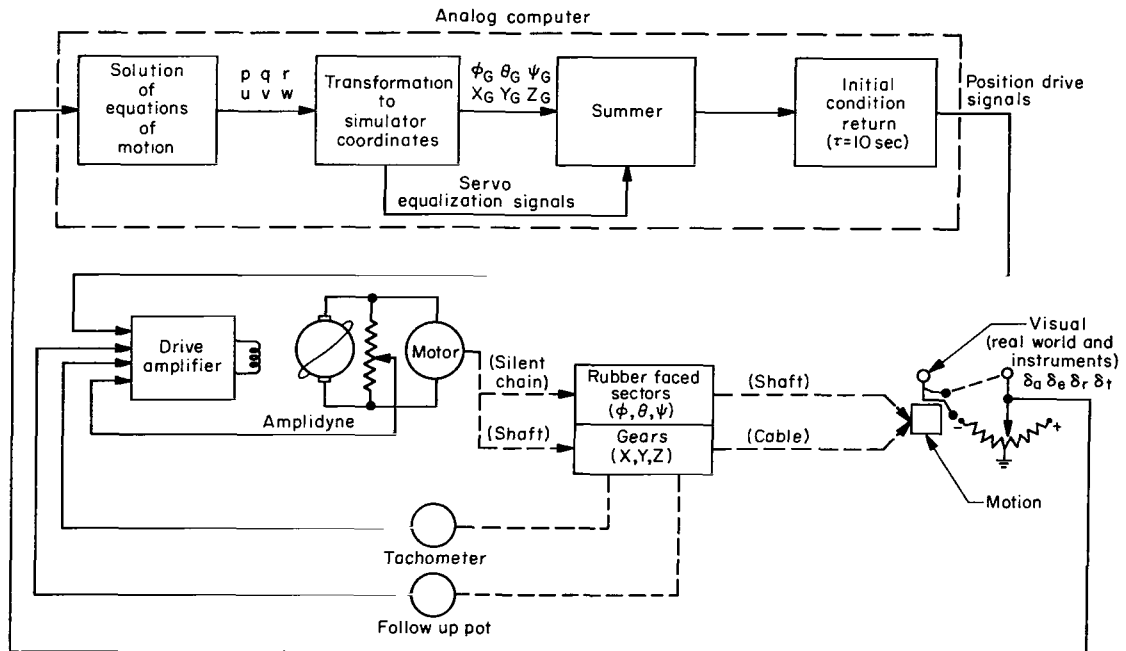


Figure 2.- Six-degrees-of-freedom simulator drive system.

## EVALUATION PROGRAMS

The simulator's usefulness for VTOL hover simulations was evaluated on the basis of how accurately it could reproduce the results from a flight program conducted at Ames with the Bell X-14A jet-lift VTOL aircraft. There were several advantages to this approach. First, the aircraft had been used at Ames for several VTOL hover studies and was reasonably well documented. Second, the aircraft was available for concurrent flights to permit direct comparison with the simulation. Finally, and perhaps most important, the same pilots were available for flying both the aircraft and the simulation, thus eliminating an otherwise troublesome variable - that of pilot technique.

In addition to the comparisons with flight, the simulator was evaluated with respect to its ability to produce results superior to those obtained from one- and two-degrees-of-freedom simulations. The latter was obtained from two sources: the subject simulator with appropriate degrees of freedom "locked-out," and an early Ames simulator with only two degrees of freedom.



## Simulation of the X-14A Aircraft

Airplane inertial and aerodynamic characteristics.- The equations of motion that were programmed on the computer are presented in appendix B. All dynamic terms were included, but the simulation of aerodynamic terms was limited to linear and angular rate damping, the latter of which was a primary program variable. Rolling, pitching, and yawing moments due to translational velocity were considered negligible at the maximum speeds attained during the simulator program. Unpublished full-scale wind-tunnel results for the X-14A indicate that these terms do not become significant until velocities of approximately 15 ft/sec are reached, and the simulator velocities rarely exceeded one-half that value, even during maximum performance translation maneuvers.

Cockpit controls.- The simulator cab (fig. 3) was designed to be functionally identical to the X-14A cockpit. The controls consisted of a conventional center-stick for control of roll and pitch, rudder pedals for yaw control, and a fighter-type throttle quadrant for height control. The mechanical characteristics of the pilot's controls (table II) were set to match those of the X-14A, but no effort was made to duplicate all geometric details. Pilot comments indicated the latter to be of secondary importance for these tests.

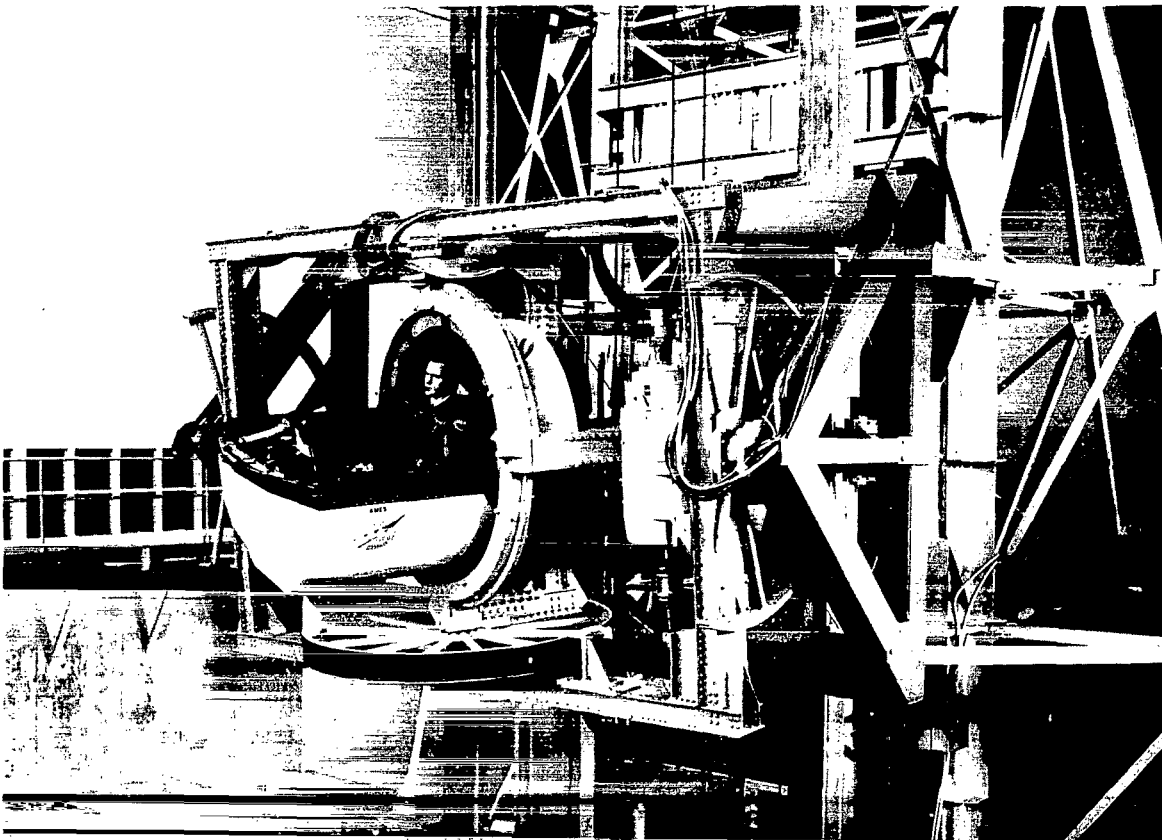


Figure 3.- Cab and gimbal structure of Ames six-degrees-of-freedom simulator.

Cockpit displays.- The instrument panel (fig. 4) was fairly conventional except for the cathode-ray tube (at the top-center position), which provided a quasi-three-dimensional display of cab position with respect to linear limits of travel.

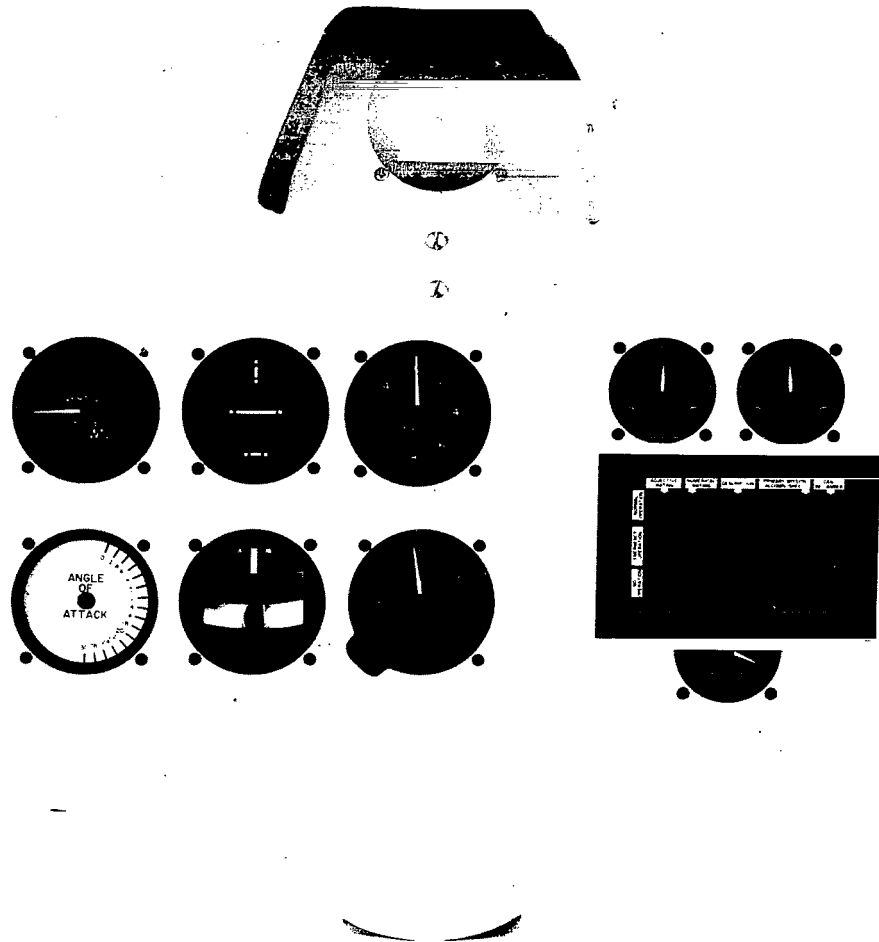


Figure 4.- Instrument panel.

## Experiments

Scope.- The scope of the simulation program is outlined in table III, and the evaluation tasks are defined in table IV. The simulator and flight programs were as identical as possible with respect to conditions and evaluation tasks. The ranges of variables used in flight were, of course, limited to those attainable by the X-14A.

The roll and pitch axes were investigated for the purpose of quantitative comparison with flight. The yaw and vertical modes were evaluated primarily in a qualitative sense. Each axis was evaluated with the simulator motion activated in all six degrees of freedom. In addition, the roll axis was

evaluated with only the roll and lateral motions activated, and then with only the roll motion so that the effects of limiting the degrees of motion freedom could be assessed.

Procedure.- The roll and pitch axes were investigated in a manner consistent with that of reference 3. Control power and damping values were varied for one axis at a time, while values for the other axes were maintained at levels adequate for a pilot rating of 3-1/2 or better. Maximum control deflection was constant (table II), and control sensitivity was allowed to vary as a function of control power. Combinations of control power and damping were evaluated in a random sequence. Pilots were occasionally told the values for a particular combination, but not until the evaluation task had been completed and a pilot rating recorded. Pilots assigned ratings according to the pilot opinion system in table V.

Two NASA test pilots participated in the simulator and flight programs. One of these pilots had participated in the flight investigation reported in reference 3. For the roll axis, each pilot established base data consisting of approximately 100 test points. The pitch axis and the two-degrees-of-freedom programs were not as extensive. One pilot completed a matrix of approximately 60 points for each of these phases, and the other pilot made spot checks for verification.

For the roll axis, the concurrent flight study was essentially a repeat of the flight study reported in reference 3. The original plan had been to compare the simulator results directly with those of reference 3, with only a few concurrent flights for memory refreshment. However, the simulator roll-control power requirements for  $PR = 3-1/2$  were almost 30 percent less than those indicated by the early flight study. After a thorough examination of the simulation failed to uncover any errors, and when pilots commented during refresher flights that the maximum roll-control power felt much less than the  $2.05 \text{ rad/sec}^2$  which was apparently available during the earlier flights, it was decided to recalibrate the X-14A in hopes of resolving the disagreement. Flight recalibration indicated the maximum roll capability of the X-14A to be  $1.6 \text{ rad/sec}^2$ , and only  $1.4 \text{ rad/sec}^2$  was required for  $PR = 3-1/2$  (at optimum damping) instead of  $1.75 \text{ rad/sec}^2$  as indicated by the earlier flight data. This resulted in a much more reasonable agreement between simulator and flight, and a decision was therefore made to gather new data from the concurrent flights for comparisons in roll. (The flight investigation of the pitch axes was not similarly repeated, because a recalibration indicated no differences from the data of ref. 3. However, ref. 3 lacked sufficient data to define a  $PR = 6-1/2$  boundary, so that part was repeated during the concurrent flights.)

As for the differences between new and old flight results, it was subsequently established that between the two investigations: (1) an undetermined decrease in reaction control bleed air occurred as the result of an engine change which decreased the RPM required for hover, and (2) the X-14A moment of inertia in roll increased about 20 percent as a result of various structural modifications. The combined effect of these changes explains the control power loss shown by the recalibration.

In answer to why less roll control power was demanded in the recent flight tests, it seems reasonable to assume that (1) the increased inertia of

the X-14A made it significantly less susceptible to disturbances, and (2) the pilots were more proficient in VTOL flight as a result of the experience gained over the intervening years. (Another factor that may have contributed to the discrepancy is that the earlier X-14A contained high breakout friction in its roll control system. Reference 3 reports this friction to be 2.0 lb, but later investigation indicated that this was probably a minimum. The lateral control system has since been equipped with hydraulic boost, and static friction has decreased to 0.5 lb.)

### Corrections

The frequency response of the simulator was measured before and after the evaluation program to determine whether changes in simulator performance had occurred that might invalidate the results. Some changes were found, but a reappraisal of the response of each axis indicated that deficiencies in the basic performance of the longitudinal and lateral drive systems which were present throughout the evaluation were more significant than the changes that occurred during the evaluation. Improvements in servo equalization for these two systems were therefore developed, and a limited matrix of approximately 20 test points was repeated by both pilots to determine the effects of these improvements on the base data. The only significant change was a reduction in the angular-rate damping required, and the base data were altered accordingly before inclusion in this report.

## RESULTS AND DISCUSSION

This section deals primarily with the comparison of six-degrees-of-freedom simulator results with X-14A flight results. Quantitative comparisons are presented for the roll-lateral and pitch-longitudinal axes. Qualitative comparisons are presented for all axes. The latter are discussed as they apply to each axis specifically, or to the entire simulation in general, whichever is appropriate.

Also included is a short discussion of results from a brief series of tests to determine whether good correlation with flight can be obtained from simulators with less than six-degrees-of-freedom. Roll-axis data from flight are compared with one-degree- (roll motion only), two-degrees- (roll and lateral), and six-degrees-of-freedom simulator data.

### Comparison of Simulator and Flight

Roll-lateral axis.- Simulator roll-axis results are compared with flight data in figure 5. Combinations of control power and damping that resulted in pilot ratings of 3-1/2 and 6-1/2 are presented in the form of bands within which pilot rating is essentially constant. In general, the simulator results correlated well with flight. Differences that did emerge are enumerated below, with possible explanations.

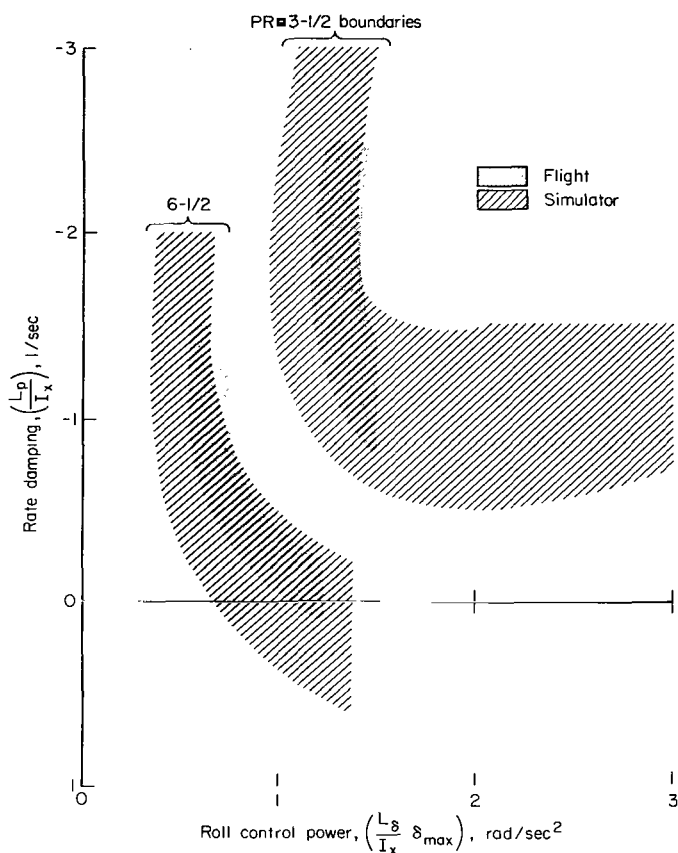


Figure 5.- Comparison of roll-axis data from six-degrees-of-freedom simulator and flight.

1. The simulator consistently required slightly less control power than flight for a pilot rating of 3-1/2. This was likely a result of the absence of external disturbances in the simulator. The aircraft, on the other hand, was affected by recirculation of the engine exhaust and other random flow disturbances, although every attempt was made to select ideal gust-free flight conditions. The discrepancy could also have a psychological basis in the pilot's knowledge of the inherent safety of the simulator, for he apparently was satisfied with lower reserves for safety.

It is probable that a greater decrease in control power would have been indicated by the simulator if it were not for the travel restriction on the maneuvering task itself. The necessity of controlling lateral position within a distance of less than 18 feet means overshoots that might go unnoticed in flight were critical in the simulator. An attempt was made to duplicate the simulator maneuvering task with the X-14A by keeping the

aircraft centerline within 18-foot limits during quick-stop maneuvers. This distance proved to be unrealistically small, and approximately 60 feet (two wing spans) was determined as the minimum maneuvering space required to interrogate the control system properly in flight. The simulator maneuvering task, therefore, was considered to be more demanding than its counterpart in flight.

2. Correlation with flight was not as good for the 6-1/2 pilot rating boundary as for the 3-1/2 boundary. The pilot's knowledge of the inherent safety of the simulator is undoubtedly a greater influence here, considering that the 6-1/2 pilot rating boundary is so dangerous to explore in actual flight.

3. The pilots reported a higher workload for the simulator spot-hovering task than for flight; that is, the pilot was "busier" in the simulator (making high-frequency, low-amplitude inputs) than he was in the airplane while hovering over a predetermined spot on the ground. The major reason seemed to be low-frequency servo lags in the simulator drive system, and a slight increase in roll damping required for hover was reflected in the data.

4. As evidenced in figure 5, the simulator data have a wider band of uncertainty than do the flight data. This is probably because of a greater population sampling rather than a peculiar characteristic of the simulator. However, the fact that scatter is present in either case seems inevitable for tests of this type because of differences in pilot backgrounds. For example, pilots with experience in transport aircraft and large helicopters are more likely to accept less maneuvering capability than pilots with jet-fighter experience. These differences manifest themselves more in the  $PR = 3-1/2$  area, where the pilot is concerned about how well he can perform the tasks, than in the  $PR = 6-1/2$  region, where the pilot is more concerned with whether he can maintain control.

Pitch-longitudinal axis.— The correlation of simulator and flight pitch-axis data was very good, as can be seen in figure 6. Control power and damping combinations required for pilot ratings of 3-1/2 and 6-1/2 are shown. (Data were insufficient to define a  $PR = 6-1/2$  boundary when reference 3 was prepared, and these flight data are presented for the first time.) There were minor deviations, as in the roll-axis comparison, and again the simulator

required slightly less control power for  $PR = 6-1/2$ . Also, for  $PR = 3-1/2$ , the simulator required more control power for lightly damped configurations.

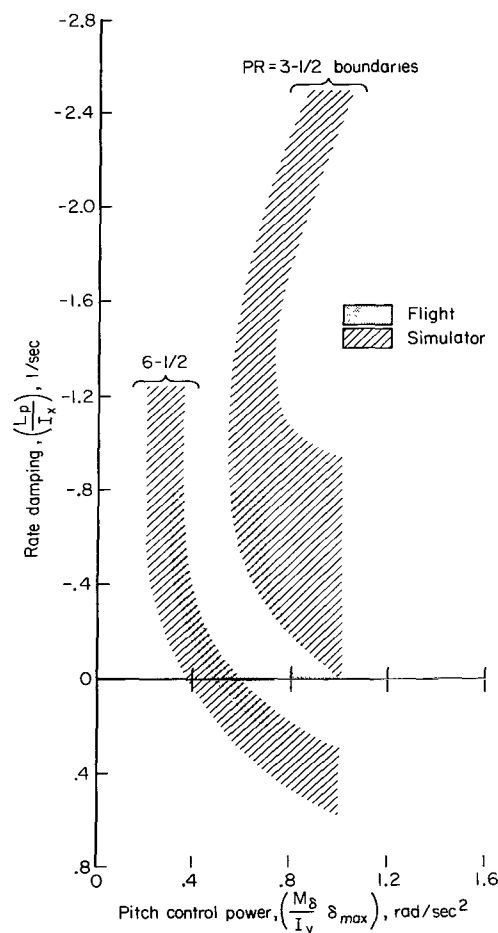


Figure 6.— Comparison of pitch-axis data from six-degrees-of-freedom simulator and flight.

Despite the good data correlation shown in figure 6, the usefulness of the simulator in evaluating pitch motions was criticized for the following reasons: First, the simulator pitch task necessitates approaching objects at the extremities of the travel limits in a head-on manner (or worse yet, tail-on), so that position and closure rates are difficult to judge. The simulator roll task, on the other hand, involves looking toward objects ahead of the cab while moving laterally, and speed and distance relationships can be judged quite accurately. Also, the pilot is reluctant to develop high rearward velocities because of poor visibility in that direction. While this problem is also common to flight, it is compounded on the simulator by the restriction imposed by the aft travel stops. Because of the difficulty in utilizing the available longitudinal maneuvering space, the pilots judged that the simulator was not so well suited for evaluating pitch as for roll.

Yaw axis.- Although yaw motion was considered beneficial to the overall simulation, the yaw control task did not appear to be extremely realistic during the limited evaluation of it. This was primarily due to its restricted travel of  $\pm 45^\circ$ , not all of which was fully usable. At yaw angles greater than  $30^\circ$ , the pitch gimbal frame so dominated the pilot's field of view that it was disorienting. Consequently, it does not appear feasible to attempt VFR tasks requiring more than  $\pm 30^\circ$  yaw displacement.

Vertical axis.- Good height control characteristics were responsible for much of the realism of the simulator. Motions were very smooth, and the pilot's workload in controlling height was judged to be nearly identical to that in flight. Control sensitivity, with the conventional fighter-type throttle quadrant controller, was set at approximately  $7.0 \text{ ft/sec}^2/\text{in}$ . This sensitivity was considered to be near optimum for the conditions of the six-degrees-of-freedom simulator, but was slightly less than the optimum for situations in which essentially unrestricted vertical motion was available (ref. 4). No attempt was made to determine optimum height control sensitivity in the flight tests.

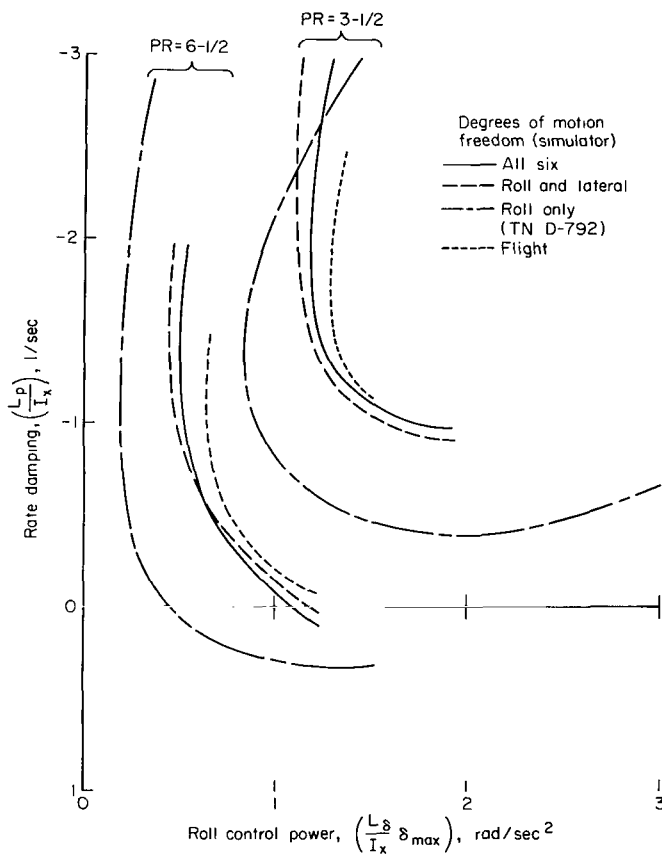


Figure 7.- Comparison of roll-axis data from various degrees of freedom motion simulators and from flight.

### Limited Axes Operation

The roll-axis evaluation was repeated, in abbreviated form, with only the roll and lateral simulator motions. These results were then compared with single-degree-of-freedom data (roll motion only) from reference 5, and with the simulator and flight data discussed in the preceding sections. Figure 7 presents these data as faired lines rather than bands to facilitate comparison with the previously published single-axis data.

Figure 7 clearly shows that the increased realism created by added degrees of simulator motion resulted in closer correlation with flight results. The plot also indicates that one angular motion and the appropriate linear motion yields essentially the same results as six-degrees-of-freedom motion. The addition of pitch-lateral and height motions helped, but the major cue lacking in the one-degree simulation was the lateral motion that occurs with a change in roll attitude. Therefore, if the objective of a simulation is solely to optimize control-system parameters about the roll axis,

at least two-degrees-of-freedom motion (roll and lateral) are required, and anything more than those two degrees is probably unnecessary.

### General Motion Characteristics

The overall motion characteristics of the simulator, according to pilots' comments, closely resembled the motions of actual hovering flight. Factors considered essential to the success of the simulation were: horizontal acceleration corresponding to a given pitch-roll attitude, pilot-vehicle dynamic coupling, realistic pilot workload, smoothness of operation, and the real-world visual scene. The most consistent pilot comments are discussed briefly in the following paragraphs.

Individual operation of either the lateral or the longitudinal mode resulted in considerable shaking and vibration caused by a perceptible roughness of mechanical drive components, structural dynamic mode excitation (primarily from dynamics of the tower structure, which can be seen in the bode plots discussed in appendix A), and the rumble of steel rollers against steel tracks. Under combined-mode operation, the task of controlling all six degrees-of-freedom masked the effect of the vibrations to a level of acceptable smoothness. The vertical linear motion and all rotational motions were exceptionally smooth.

Certain combinations of control power and damping resulted in pilot-vehicle dynamic coupling, which was the subject of repeated pilots' comments. One of these was incipient or borderline, pilot-induced oscillations that occurred with combinations of high control power (high sensitivity) and low damping. This type of dynamic coupling could not be properly investigated with a simulator that was nonmoving or that had only angular motions. Unfortunately, flight correlation for most of these conditions was not possible because of the limited control power capability of the X-14A airplane.

At the other end of the spectrum, the low-frequency wallowing motions characteristic of low-control-power configurations of the X-14A were realistically reproduced on the simulator. Here, however, the restricted linear limits hindered control-system evaluation. The pilot would sometimes drift into the limit stops, causing the computation to stop (and an automatic return of the simulator to its initial condition) before he could determine whether a recovery might have been possible in flight.

Another frequently recurring point seemed to confirm the ability of the simulator to correlate with flight. Whenever the pilot commented that a simulator control configuration felt similar to that of a particular VTOL aircraft he had flown, investigation invariably revealed that the control-system characteristics were essentially identical.



## Visual Scene

The feature of the simulator that is largely responsible for its good motion fidelity (i.e., simulator motions scaled one-to-one with computed motions) also makes possible the use of the real world for a visual scene. Problems that normally plague artificial visual presentations, such as resolution, color, field of view, and perspective, were thus avoided. The cab (fig. 3) was not enclosed, and the pilot performed the VTOL hovering tasks (table IV) by visual reference to remain within the allowable travel envelope.

An important consideration in the overall effectiveness of the simulator was the provision of visual aids that enabled the pilot to utilize as much of the available maneuvering space as possible. Colored styrofoam balls suspended by ropes in front of the simulator marked the travel limits in the Y-Z plane, and also helped the pilot to determine the forward limit. A cathode-ray tube mounted on the instrument panel (fig. 4) provided a quasi-three-dimensional position display. (This display was used more as a cross-check with exterior visual cues rather than as a primary position indicator.)

The only unrealistic aspect of the visual scene was that created by the necessity to hover very close to large immovable objects (interior hanger walls, ceilings, etc.). This aspect was offset by the expanded outdoor view made possible by opening large doors that extend across the front of the simulator. This view and the resulting fresh-air environment were effective in dispelling the feeling of confinement usually associated with indoor ground-based simulators.

## CONCLUDING REMARKS

Pilot opinion data obtained from the simulator and from flight correlated very well for tasks limited to small maneuvers associated with hovering flight. The travel envelope of the simulator was considered adequate for quick stops, precision hovering, and takeoffs and landings without the need for motion washouts.

The overall quality of simulator motions imparted the important sensations of being supported in hovering flight, and the real-world visual scene effectively dispelled the feeling of confinement within a small enclosed area. The pilot workload also was comparable to that in flight.

The linear travel and acceleration limits of the simulator proved somewhat restrictive. Increased room to interrogate control-system response was desirable and slightly higher linear acceleration capability would more effectively utilize the existing maneuvering space.

When roll-axis maneuvers were evaluated, essentially the same results were obtained with only roll and lateral motions as were obtained with six-degrees operation.

The simulator appears to be well suited for studies involving the optimization of VTOL control-system parameters. Final verification of promising systems should be accomplished through evaluation in flight; however, the piloted ground simulation technique will permit the range of test variables for those flight test to be much better defined and will also provide valuable pilot orientation. Thus, the efficiency and safety of follow-on flight evaluation will be considerably increased.

Ames Research Center

National Aeronautics and Space Administration

Moffett Field, Calif., 94035, March 25, 1969

## APPENDIX A

### FREQUENCY RESPONSE CHARACTERISTICS OF THE AMES

#### SIX-DEGREES-OF-FREEDOM MOTION SIMULATOR

To record total system response, which included both the drive system dynamics and the structural dynamics, angular and linear accelerometers appropriate for each axis of motion were installed in the cab. The linear accelerometers were located close to the center of rotation in order to minimize the correction for angular cross-coupling when all six degrees of freedom were in motion. For the frequency response tests, the need for corrections was eliminated completely by activating only one degree of freedom at a time.

Bode plots of system response without external compensation were prepared from accelerometer recordings of the roll, pitch, longitudinal, and lateral axes. These records indicated third- or fourth-order systems, except for the roll axis, through the frequency range of 0 to 12.5 rad/sec. (Frequencies higher than 12.5 rad/sec were not considered useful because of roughness due to structural-mode excitation.) Roll-axis response was approximated by a first-order transfer function.

Compensation terms were selected on the basis of the foregoing and verified by accelerometer recordings. The bandwidth, defined as the frequency range within which a phase lag of  $20^\circ$  is not exceeded, was extended to 7.0 rad/sec or better for all axes except roll, which was extended to 5.2 rad/sec. The compensation terms are rate and acceleration feed-forward loops obtained from the computation of the equations of motion, and added to the position command signals.

Figures 8 through 11 contain bode plots of both the uncompensated and the compensated response measurements, together with the approximate transfer functions for each.

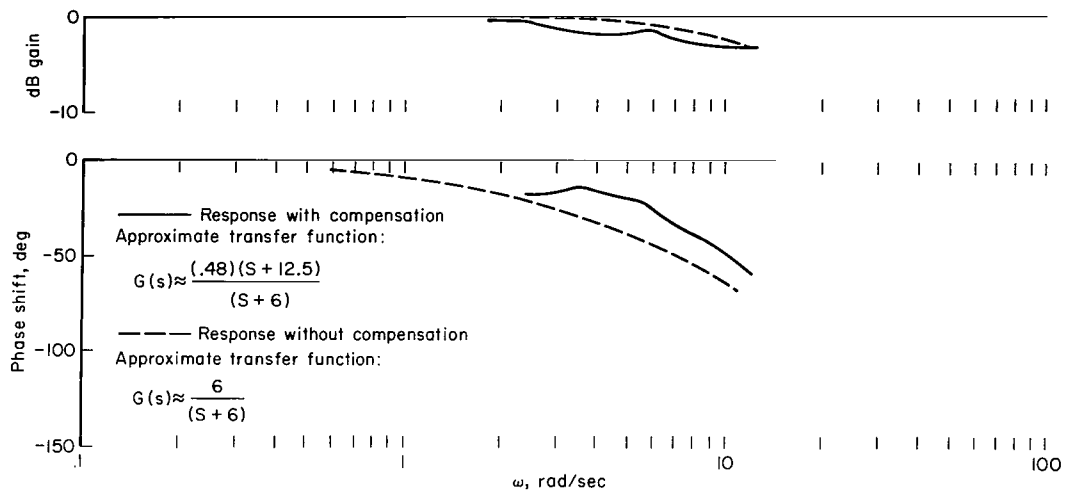


Figure 8.- Roll-axis response of six-degrees-of-freedom simulator.

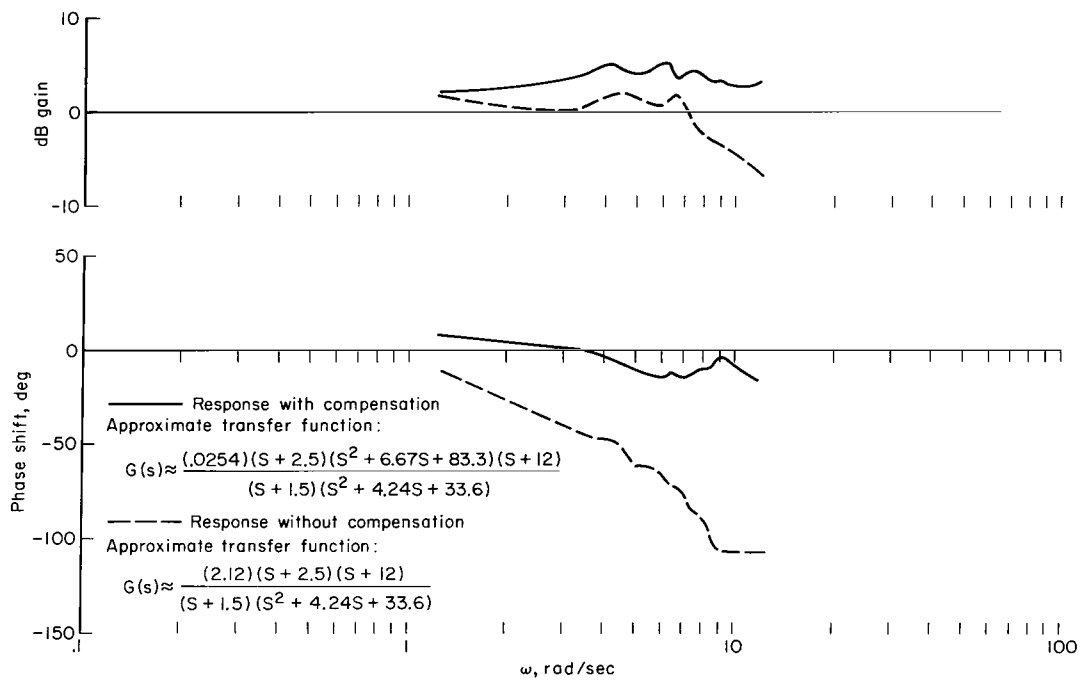


Figure 9.- Pitch-axis response of six-degrees-of-freedom simulator.

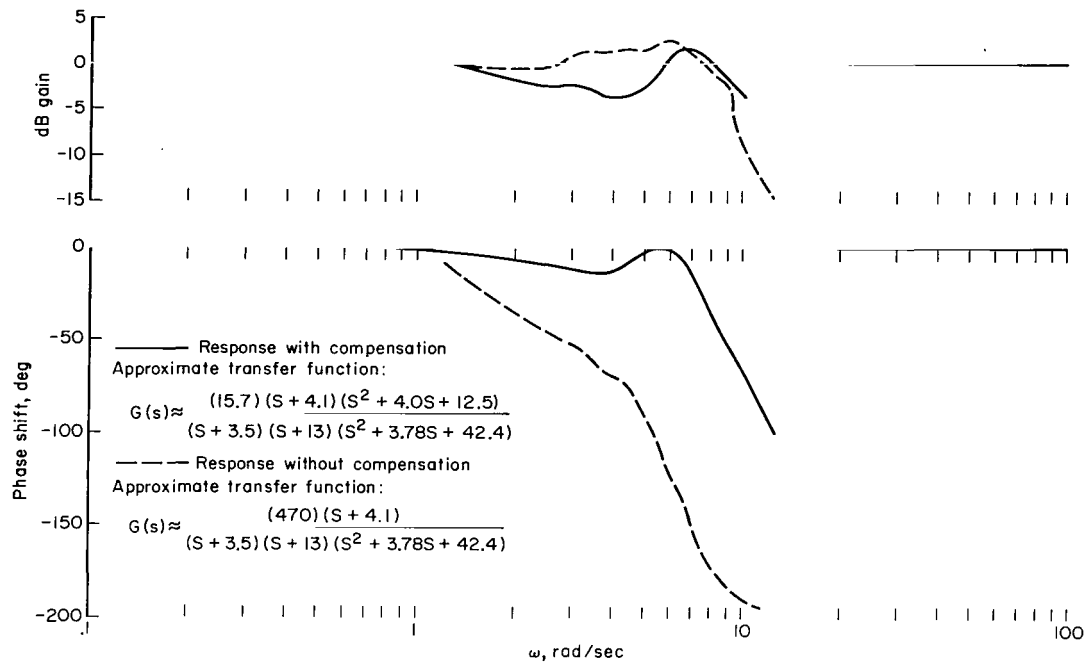


Figure 10.- Longitudinal-axis response of six-degrees-of-freedom simulator.

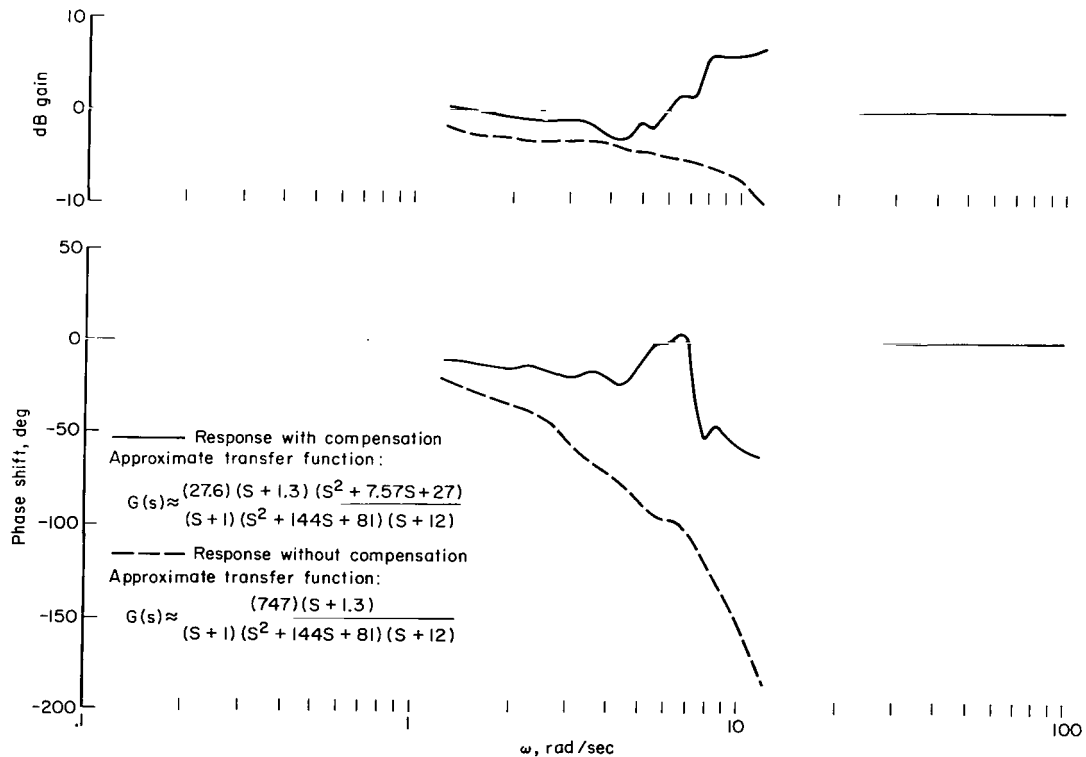


Figure 11.- Lateral-axis response of six-degrees-of-freedom simulator.

## APPENDIX B

### AIRPLANE EQUATIONS OF MOTION AND ANGULAR CONVERSIONS

The following equations were programmed on a general purpose analog computer. The equations were first solved using the body-axes system, and then transformed to the simulator-axes reference frame. The equations were simplified by small-angle approximations.

#### Linear Accelerations

$$\dot{u} = rv - qw - g\theta$$

$$\dot{v} = pw - ru + g\phi$$

$$\dot{w} = qu - pv + g - (T_z/m) - C_z w^2$$

where  $T_z$  = thrust along vertical body axis (force up, positive), lb

$C_z$  = vertical velocity "damping coefficient" to approximate X-14A

#### Angular Accelerations

$$\dot{p} = \frac{L_{\delta_a} \delta_a + L_p p}{I_x} - \left( \frac{I_z - I_y}{I_x} \right) qr + \frac{I_{xz}}{I_x} (\dot{r} + pq)$$

$$\dot{q} = \frac{M_{\delta_e} \delta_e + M_q q}{I_y} - \left( \frac{I_x - I_z}{I_y} \right) rp + \frac{I_{xz}}{I_y} (r^2 - p^2)$$

$$\dot{r} = \frac{N_{\delta_r} \delta_r + N_r r}{I_z} - \left( \frac{I_y - I_x}{I_z} \right) pq + \frac{I_{xz}}{I_z} (\dot{p} - qr)$$

#### Euler Angles

$$\dot{\phi} = p + \theta(q\phi + r)$$

$$\dot{\theta} = q - r\phi$$

$$\dot{\psi} = q\phi + r$$

### Inertial-Axes Displacements

$$\dot{X} = u \cos \psi + v(-\sin \psi) + w(\theta \cos \psi + \phi \sin \psi)$$

$$X = \int \dot{X} dt + K_{\dot{X}} \dot{X} + K_{\dot{u}} \dot{u}$$

$$\dot{Y} = u \sin \psi + v \cos \psi + w(\theta \sin \psi - \phi \cos \psi)$$

$$Y = \int \dot{Y} dt + K_{\dot{Y}} \dot{Y} + K_{\dot{v}} \dot{v}$$

$$\dot{Z} = u\theta + v\phi + \dot{w}$$

$$Z = \int \dot{Z} dt + K_{\dot{Z}} \dot{Z}$$

where, for servo compensation  $K_{\dot{X}} = 0.32$ ,  $K_{\dot{u}} = 0.08$  (assuming  $\dot{u} \approx \ddot{x}$ )  
 $K_{\dot{Y}} = 0.28$ ,  $K_{\dot{v}} = 0.037$  (assuming  $\dot{v} \approx \ddot{y}$ )  
 $K_{\dot{Z}} = 0.5$

### Gimbal-Angle Conversions

$$\phi_G = \phi - \theta \frac{\sin \psi}{\cos \psi} + K_{\dot{\phi}} \dot{\phi}$$

$$\theta_G = \frac{\theta}{\cos \psi} + K_{\dot{\theta}} \dot{\theta} + K_{\dot{q}} \dot{q}$$

$$\psi_G = \psi$$

where, for servo compensation  $K_{\dot{\phi}} = 0.08$  (assuming  $\dot{\phi} \approx \dot{\phi}_G$ )  
 $K_{\dot{\theta}} = 0.08$ ,  $K_{\dot{q}} = 0.012$  (assuming  $\dot{\phi} \approx \dot{\phi}_G$ ,  
 and  $\dot{q} \approx \ddot{\theta}_G$ )

## REFERENCES

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3. Rolls, L. Stewart; and Drinkwater, Fred J., III: A Flight Determination of the Attitude Control Power and Damping Requirements for a Visual Hovering Task in the Variable Stability and Control X-14A Research Vehicle. NASA TN D-1328, 1962.
4. Gerdes, Ronald M.; and Weick, Richard F.: A Preliminary Piloted Simulator and Flight Study of Height Control Requirements for VTOL Aircraft. NASA TN D-1201, 1962.
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TABLE I.- AMES SIX-DEGREES-OF-FREEDOM SIMULATOR MOTION CAPABILITIES

Motion generated	Limits		
	Displacement	Velocity	Acceleration
Roll	$\pm 45^\circ$	3.8 rad/sec	12 rad/sec <sup>2</sup>
Pitch	$\pm 45^\circ$	2.3 rad/sec	6 rad/sec <sup>2</sup>
Yaw	$\pm 45^\circ$	4.1 rad/sec	7 rad/sec <sup>2</sup>
Longitudinal	$\pm 9.1$ ft	11.4 ft/sec	6 ft/sec <sup>2</sup>
Lateral	$\pm 9.1$ ft	11.4 ft/sec	7 ft/sec <sup>2</sup>
Vertical	$\pm 8.4$ ft	13.2 ft/sec	10 ft/sec <sup>2</sup>

TABLE II.- CONTROL-SYSTEM MECHANICAL CHARACTERISTICS

Axis	Maximum control deflection, in.	Static friction, lb	Force gradient, lb/in.
Roll	$\pm 5.0$	+0.19 -.44	<div style="text-align: center;"> 0  ↓ </div>
Pitch	$\pm 6.0$	+.25 -1.06	
Yaw	$\pm 3.0$	$\pm 6.0$	
Vertical	+6.2	(a)	

<sup>a</sup>Adjustable by the pilot.

TABLE III.- SCOPE OF TESTS

Axis investigated	Degrees of motion freedom used	Range of variables	Primary purpose of investigation
Roll	All six	Control power: 0.25 to 4.0 rad/sec <sup>2</sup> Aircraft damping: +1.0 to -4.0 1/sec	Qualitative and quantitative comparison with flight
Roll	Roll and lateral only	Control power: 0.25 to 4.0 rad/sec <sup>2</sup> Aircraft damping: +1.0 to -3.0 1/sec	Qualitative and quantitative comparison with 6°-sim, 2°-sim, and 1°-sim
Pitch	All six	Control power: 0.25 to 1.5 rad/sec <sup>2</sup> Aircraft damping: +1.0 to -2.0 1/sec	Qualitative and quantitative comparison with flight
Yaw	All six	Control power: 0.25 to 2.0 rad/sec <sup>2</sup> Aircraft damping: 0 to -1.5 1/sec	Qualitative comparison with flight
Vertical	All six	Control power: 1.5 to 10.5 ft/sec <sup>2</sup> Aircraft damping: fixed per X-14A	Qualitative comparison with flight

TABLE IV.- SIMULATOR PILOT'S TASKS FOR ROLL AND PITCH AXES

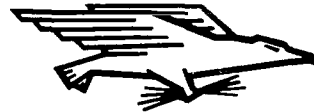
<p>Precision hover: (minimum time, 30 sec)</p>	<p>Steady hover over a spot, maintaining position within approximately <math>\pm 1</math> or 2 ft. Simulated VTOL takeoff and landing. Possible pilot-induced upsets as an additional check on hovering steadiness.</p>
<p>Maneuver: (average time for maneuver, 45 sec)</p>	<p>Translate as rapidly as possible from one edge of pit to the other and return, then over and back a second time. This maneuver was evaluated with respect to precision of control, and tendency to overshoot or to induce oscillation.</p>

TABLE V.- PILOT-OPINION RATING SYSTEM

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only <sup>1</sup>	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition <sup>1</sup>	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

<sup>1</sup>Failure of a stability augments.

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